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# A High-Efficiency Photonic Nanowire Single-Photon Source Featuring An Inverted Conical Taper

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**Abstract**—A photonic nanowire single-photon source design incorporating an inverted conical tapering is proposed. The inverted taper allows for easy electrical contacting and a high photon extraction efficiency of 89 %. Unlike cavity-based approaches, the photonic nanowire features broadband spontaneous emission control and an improved tolerance towards fabrication imperfections.

**Keywords**—photonic nanowire; single-photon source; inverted conical tapering; electrical pumping.

## I. INTRODUCTION

The solid-state single-photon source (SPS) is a key component in the field of quantum information processing [1]. Here, a photon extraction efficiency  $\varepsilon$  close to 100 % is desired, where  $\varepsilon$  is defined as the number of detected photons in the collection optics per trigger. Assuming a perfect radiative yield, the efficiency is defined as  $\varepsilon = \beta\gamma$  [2], where  $\beta$  is the fraction of spontaneous emission coupled from the photon emitter to the optical mode of interest and  $\gamma$  is the power collected by the collection optics relative to the power of the optical mode. In the microcavity SPS, the Purcell effect is employed ensure a high  $\beta$ , however this approach is highly sensitive to fabrication imperfections, limiting  $\varepsilon$  to 44 % [3].

Recently, we demonstrated an optically pumped SPS based on a quantum dot (QD) in a photonic nanowire with a regular conical tapering featuring a record-high efficiency of 72 % [4]. Unlike cavity-based SPS designs, a geometrical effect ensures a  $\beta > 90$  % over a broad 70 nm wavelength range. This tolerance relaxes fabrication constraints and allows for broadband emission control. However, the regular taper is defined using a serial ion beam etching process and is incompatible with direct electrical contacting. To address these issues, we propose in this work a photonic nanowire design incorporating an inverted conical tapering allowing for both parallel processing and easy electrical contacting [5].

## II. NANOWIRE SPS DESIGN

We study the GaAs nanowire with an embedded QD emitting light at 950 nm sketched in Fig. 1. The metal contact sections are electrically isolated by air and the GaAs nanowire is doped to create a *p-i-n* diode.

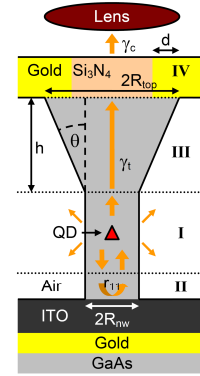


Figure 1. Photonic nanowire design with an inverted conical taper.

The SPS consists of four separate elements. Element I is the nanowire incorporating a QD emitting photons predominantly into the  $HE_{11}$  mode. Half of these propagate downwards, so we include the metal mirror in element II to reflect this light back towards the top. In the central element III, the  $HE_{11}$  mode profile is adiabatically expanded with the purpose of obtaining a low output beam divergence. Finally, element IV features an annular gold contact and a central anti-reflection coating.

Following [6] we employ an elements-splitting approach to compute the total efficiency  $\varepsilon$ . Here  $\varepsilon$  is given by [6]

$$\varepsilon = \beta\gamma \frac{(1 + |r_{11}|)^2}{2(1 + \beta|r_{11}|)}, \quad (1)$$

where  $r_{11}$  is the modal reflectivity of the metal mirror and  $\gamma = \gamma_c\gamma_t$  is the transmission through the inverted taper and the top contact sections. The fraction on the RHS of (1) is a correction taking into account the reflectivity of the metal mirror.

Using the elements-splitting approach we can study and optimize the four elements individually and subsequently evaluate the total efficiency  $\varepsilon$  using (1). The simulations are performed using the eigenmode expansion technique [7] and the tapering section is modeled using a staircase approximation.

### III. INVERTED CONICAL TAPER

The novel feature of our electrically pumped nanowire SPS design is the inverted taper of element III. Whereas a conical taper expanding the  $HE_{11}$  profile into air is employed in the optically pumped nanowire design [4,6], our new SPS design features an inverted tapering which instead expands the mode inside the nanowire [5]. The taper is illustrated in Fig. 2(a).

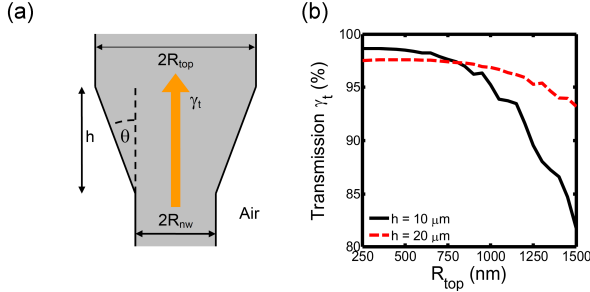


Figure 2. The inverted taper element III (a) and the transmission  $\gamma_t$  for two different taper heights  $h$  as function of  $R_{top}$  (b).

The modal transmission through the taper element is shown in Fig. 2(b) as function of the top nanowire radius  $R_{top}$  for two taper heights  $h$ . We fix  $R_{nw}$  at 120 nm to ensure a high  $\beta$  [5], and we include an absorption loss of  $\eta = 10 \text{ cm}^{-1}$  due to free-carrier scattering from  $n$ -doping. For a small  $R_{top} < 750 \text{ nm}$ , the smaller taper height  $h = 10 \text{ }\mu\text{m}$  leads to a smaller absorption loss and a slightly higher transmission than for  $h = 20 \text{ }\mu\text{m}$ . However, for  $R_{top} > 750 \text{ nm}$ , the side wall angle  $\theta$  becomes large enough to compromise the adiabaticity of the  $HE_{11}$  mode transition. For small values, the side wall angle  $\theta$  is given by  $\theta \cong (R_{top} - R_{nw})/h$  and the larger taper height  $h = 20 \text{ }\mu\text{m}$  results in a smaller side wall angle, a better preservation of adiabaticity and an improved transmission in the regime  $R_{top} > 750 \text{ nm}$ .

### IV. PREDICTED EFFICIENCY

From a calculation of the element coefficients  $\beta$ ,  $r_{11}$ ,  $\gamma_i$  and  $\gamma_c$  we can estimate the total efficiency  $\varepsilon$  of the proposed electrically-pumped SPS design. We have the liberty of choosing  $R_{top}$ ,  $h$  and  $d$ . In the following we set  $d = 100 \text{ nm}$ , and we study  $\varepsilon$  as function of  $R_{top}$  and  $h$  in Fig. 3 for a 0.8 NA lens. The figure includes results from the element-splitting approach as well as from exact calculations performed by placing a dipole in the full structure and computing the far field emission profile.

We observe that the efficiency  $\varepsilon$  increases with  $R_{top}$  towards a maximum value of  $\sim 89 \%$  obtained for  $R_{top} \sim 900 \text{ nm}$ . At this radius the collection efficiency  $\gamma_c$  is no longer improved by increasing  $R_{top}$ . A slight deviation for  $R_{top} > 750 \text{ nm}$  for the  $h = 10 \text{ }\mu\text{m}$  curves computed using the simplified and the exact models is observed. The efficiency obtained by the exact model actually increases beyond  $89 \%$  as  $R_{top}$  approaches  $1500 \text{ nm}$ , whereas  $\varepsilon$  for the simplified model clearly decreases, reflecting the drop in transmission observed in Fig. 2(b) for  $R_{top}$  approaching  $1500 \text{ nm}$ .

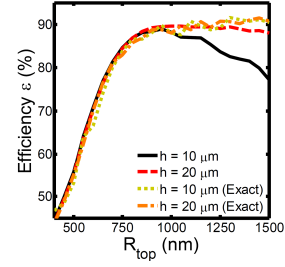


Figure 3. Total SPS efficiency  $\varepsilon$  as function of  $R_{top}$  for two different taper heights  $h$ .

This discrepancy can be understood by considering the breakdown of the adiabatic transition of the  $HE_{11}$  mode as it propagates through the inverted taper. For a fixed taper height  $h$ , the side wall  $\theta$  increases with  $R_{top}$  and for  $R_{top} > 1000 \text{ nm}$  there is significant coupling to higher order modes  $HE_{1m}$  ( $m > 1$ ). In the simplified model this coupling is treated as a loss reducing  $\varepsilon$ , however even though these higher order modes generally have a more divergent far field emission profile, a significant part of the light from these modes can be picked up by the 0.8 NA lens. The exact computation includes these higher-order contributions, and the redistribution of power to several  $HE_{1m}$  modes does not decrease  $\varepsilon$ .

### V. CONCLUSION

In this work we have demonstrated a practical design for a high-efficiency single-photon source. The central feature of the design is an inverted conical taper allowing simultaneously for easy electrical contacting and a photon extraction efficiency of  $89 \%$ .

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